REVISED ^{36}CL PRODUCTION RATES IN LUNAR ROCK 64455 USING NEW CROSS SECTION MEASUREMENTS.

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Many radionuclides and stable nuclides are produced in extraterrestrial materials by the interactions of both solar (SCR) and galactic (GCR) cosmic rays. SCR are ~98% protons having energies <200 MeV and penetrate only the top 1 - 2 cm of extraterrestrial material. GCR are ~87% protons, have higher energies, and can penetrate several meters.

An interesting radionuclide to study is ^{36}Cl ($T_{1/2}$ = 3.0 x 10^5 years) because this cosmogenic radionuclide is produced by thermal neutron capture reactions in addition to both low and high energy spallation reactions from many elements found in extraterrestrial materials. ^{36}Cl depth profiles measured in lunar cores and rocks (1,2,3) show clear evidence of production of this nuclide by solar protons in addition to GCR. However, it was difficult to interpret this data because of the lack of good cross section information for ^{36}Cl production.

One model often used to analyze the production depth profiles of cosmogenic nuclides is the Reedy and Arnold model (4), which uses thin target cross sections as input data. Estimated values are used if no reliable measured data exists. The important elements for ^{36}Cl production are Cl, K, Ca, Ti, Fe and Ni in extraterrestrial materials. Cross sections with these elements are needed to analyze ^{36}Cl production depth profiles.

As recently as 1989, so few relevant cross sections were known that it was not possible to interpret the ^{36}Cl depth profile measured in lunar core 15008 for solar proton effects (1). In 1995, preliminary cross section data (5) for the Ca(p,x) ^{36}Cl reaction were used to estimate the solar proton flux from the measured ^{36}Cl depth profile in lunar rock 64455 (2).

We report new cross section measurements made at the Harvard Cyclotron Laboratory for Ca(p,x) ^{36}Cl and K(p,x) ^{36}Cl from 40 - 160 MeV, which are generally in good agreement with those reported recently (6,7). After irradiation, Cl was separated from the targets of $CaCO_3$ and KNO_3 and ^{36}Cl was analyzed using Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory (8). Table 1 and Figures 1 and 2 show the results.

Table 1: New cross section measurements

Incident Energy MeV	**Ca(p,x) ^{36}Cl** Cross section mb	**K(p,x) ^{36}Cl** Cross section mb
158.6±1.0	15.9±0.9	
158.4±1.0		31.8±1.8
119.0±2.0	17.7±1.0	
118.8±2.0		35.8±2.0
100.7±3.0	16.6±0.9	
100.2±3.0		35.4±1.9
80.9±3.0		39.2±2.1
80.4±3.0	19.1±1.1	
70.5±3.0		42.4±2.3
70.3±3.0	17.1±0.9	
49.9±3.7		29.0±1.6
49.3±3.7	2.14±0.12	
41.9±4.4		12.6±0.7

The elemental composition of 64455 by weight, for elements that are important for ^{36}Cl production, is 9.4% Ca, 4.7% Fe, 0.3% Ti and 0.1% K. Using all reported new cross section values including those reported here, it is estimated that ~96%, ~3.8%, ~0.2% and ~0.1% of ^{36}Cl production in the surface is from Ca, K, Ti and Fe, respectively. For this and most other lunar rocks, Ca is the most important target for ^{36}Cl production.

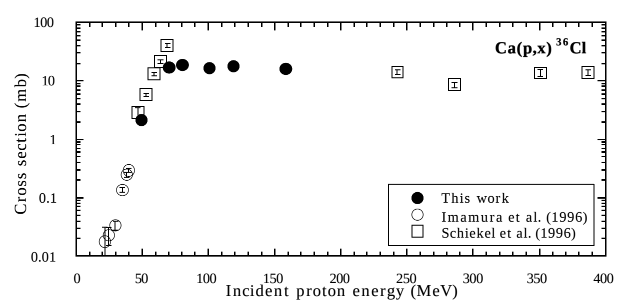

Fig. 1. Ca(p,x) ^{36}Cl cross sections. Errors are as shown or are smaller than the plotted symbol.

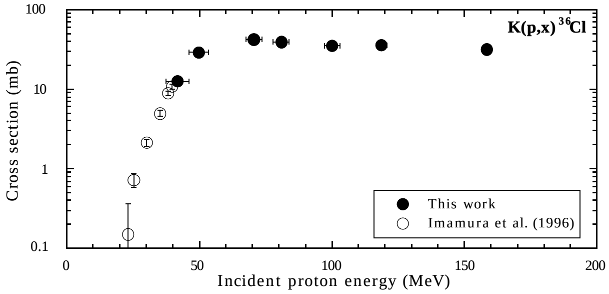

Fig. 2. K(p,x) ^{36}Cl cross sections. Errors are as shown or are smaller than the plotted symbol.

For 64455, the contribution to the ^{36}Cl production rate from K is small compared to that from Ca. However, for K-rich rocks, the contribution to the overall ^{36}Cl production from K can be significant. For example, in KREEP rocks (such as 15382 or 15386 with ~0.5% K), we can estimate that ~21% of the ^{36}Cl production in the surface layer is from K, now that we have the good cross section measurements presented here.

Figure 3 shows the SCR produced ^{36}Cl production rate in 64455 calculated for solar proton spectral parameters R_0 = 80 MV, J_0 = 100 p/cm^2 s (E > 10 MeV, 4π) for the three cross section data sets; N8P using values available in 1989 (1); S4P based on (5) and used in (2) in 1995; and S7P the current data set using all the recent cross section measurements including those reported here. The ^{36}Cl production rate calculated using the new cross section values (S7P) is much higher than that predicted in 1989 but is significantly lower than that estimated in 1995, when only the preliminary values for the Ca(p,x)^{36}Cl cross section reported in (5) were used. However, there are still differences in the Ca(p,x)^{36}Cl cross section measurements reported by (6) and those presented here over the important energy range for solar protons of 50 - 100 MeV. Our measurements indicate lower values for the cross sections in this energy region and so a lower production rate of ^{36}Cl by SCR. Further measurements will resolve this discrepancy.

Now that there are or soon will be good cross section measurements for these important reactions leading to ^{36}Cl production by solar protons, we can make improved estimates of the ^{36}Cl production rate in lunar rocks and then better estimates for the solar proton flux over this time period in the past.

The new cross sections will result in lower solar-proton fluxes than with the estimated cross section (N8P) used by (1) but higher fluxes than with the S4P set used in (2). Solar-proton fluxes determined from ^{36}Cl and other radionuclides in 64455 will be reported after several more cross sections are measured for ^{36}Cl in the 50-100 MeV range.

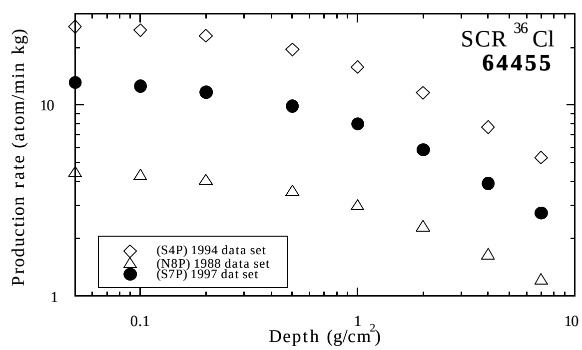

Fig. 3. Production rate of ^{36}Cl in lunar rock 64455 by SCR for R_0=80 MV, J_0=100 p/cm^2 s (E>10 MeV, 4π).

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